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Mediation of Supersymmetry Breaking via Anti-Generation Fields

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Abstract

In the context of the weakly coupled heterotic string, we propose a new model of mediating supersymmetry breaking. The breakdown of supersymmetry in the hidden sector is transmitted to anti-generation fields via gravitational interactions. Subsequent transmission of the breaking to the MSSM sector occurs via gauge interactions. It is shown that the mass spectra of superparticles are phenomenologically viable.

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The dynamical mechanism of supersymmetry(SUSY) breaking and its mediation to our visible world form the major unsolved problems of particle physics. As for the former, many models have been proposed[1]. For phenomenological implications it is of more importance to clarify how SUSY breaking is communicated to the visible sector. Two ways of transmitting SUSY breaking to the visible sector have been proposed. The first is that gravitational interactions in $N = 1$ supergravity theory play this role[2]. The second is that gauge interactions play the role of the messenger[3]. In the framework of superstring theory it seems that the gravity-mediated SUSY breaking scenario is plausible. In the context of the weakly coupled heterotic $E_8 \times E_8'$ superstring, E_8' is considered to be the hidden sector gauge symmetry. If supersymmetric gauge dynamics in the hidden sector, such as gaugino condensation, cause SUSY breaking to occur, the effects of the SUSY breaking will be transmitted to the observable sector through gravitational interactions. In these types of simple models[4], the F-components of moduli fields other than the dilaton are expected to develop their vacuum expectation values (VEVs). The gauginos acquire their soft SUSY breaking masses at one loop, but not at the tree level. As a consequence, the gaugino masses turn out to be too small compared to the soft scalar masses. Namely, we have the relations

$$m_\lambda \ll m_0 \lesssim m_{3/2} \,, \tag{1}$$

where m_λ, m_0 and $m_{3/2}$ are the gaugino mass, the soft scalar mass and the gravitino mass, respectively. This mass spectrum of superparticles is phenomenologically unacceptable. Although it has been pointed out that this problem can be solved in strongly coupled heterotic $E_8 \times E_8'$ superstring theory (M-theory)[5][6], there remains another problem regarding non-universality of the soft breaking mass parameters. Since in string theory the moduli fields are generally charged under the flavor symmetry, the soft scalar masses become flavor-dependent. As a result of these non-universal properties for the scalar masses, we are confronted with the so-called FCNC problem. With regard to this point, the gauge-mediated SUSY breaking scenario has the advantage of producing the universal soft scalar masses and then ensuring sufficient suppression of the FCNC.

In this paper we propose a new model based on the weakly coupled heterotic string on the Calabi-Yau compactification, whose superparticle mass spectrum is phenomenologically viable and which is free from the FCNC problem. The breakdown of SUSY coming from the hidden sector gaugino condensation begins by being transmitted to anti-generation fields in the observable sector via gravitational interactions. This is due to the assumption that only VEVs of the Kähler class moduli fields T acquire nonvanishing F-components. Subsequent transmission of SUSY breaking to the low-energy MSSM sector occurs via gauge interactions. Then the gaugino masses are of the same order as the soft scalar masses. In addition, due to the flavor-blind nature of gauge interactions, we obtain the universal soft scalar masses.

The four-dimensional effective theory in the observable sector from the weakly

coupled Calabi-Yau string is characterized by $N = 1$ SUSY, the E_6 gauge group, and massless matter fields which belong to $\mathbf{27}$ and $\mathbf{27}^*$ representations in E_6. The massless chiral superfields apart from E_6 singlets consist of

$$N_f\, \Phi(\mathbf{27}) \;+\; \delta\,(\Phi(\mathbf{27}) + \overline{\Phi}(\mathbf{27}^*))\,, \tag{2}$$

where N_f denotes the family number at low energies. δ sets of vector-like multiplets are included in the massless sector. The numbers $N_f+\delta$ and δ represent the generation number and the anti-generation number, respectively. These numbers coincide with the Hodge numbers h^{21} and h^{11} for the compactified manifold, respectively. We will assume $N_f = 3$ and $\delta = 1$ for the sake of simplicity. The particles beyond the MSSM are contained in $\mathbf{27}$. Namely, in $\mathbf{27}$ we have color-triplet Higgses g and g^c and a singlet S as well as the quark superfield $Q = (U, D), U^c, D^c$, lepton superfield $L = (N, E), N^c, E^c$, and Higgs doublets H_u, H_d. Moreover, there appear a dilaton field D, h^{11} Kähler class moduli fields T_i, and h^{21} complex structure moduli fields U_i. The VEV of a dilaton field D determines the gauge coupling constant, and the VEVs of the moduli fields U_i and T_i parametrize the size and shapes of the compactified manifold. In the observable sector from the Calabi-Yau string, the superpotential W contains trilinear terms in Φ and $\overline{\Phi}$:

$$W = h(U)\,\Phi^3 + f(T)\,\overline{\Phi}^3\,. \tag{3}$$

Here $h(U)$ and $f(T)$ are the appropriate holomorphic functions of the moduli fields U and T, respectively. In Eq. (3) we have omitted the generation indices. In Ref.[7] it is shown that the cubic terms of $\overline{\Phi}$ in the superpotential are corrected by instantons on the string worldsheet. It should be noted that in the Calabi-Yau string, Φ and $\overline{\Phi}$ couple separately to the U moduli and the T moduli, respectively [8]. As mentioned above, in the observable sector, the seed of SUSY breaking is expected to be a nonvanishing VEV of F^T [4], which is the F-component of the moduli field T. The F-components of the dilaton D and the moduli U are assumed to have vanishing VEVs. This situation is the same as that in the moduli-dominated SUSY breaking scenario[9]. Hereafter we denote the VEV of the moduli field T by the same letter as the field. For example, we write $\langle T\rangle = T + \theta^2\, F^T$.

In Eq. (3) the trilinear coupling of $\overline{\Phi}$ contains the terms

$$f(T)(\overline{S}\overline{H}_u\overline{H}_d + \overline{S}\overline{g^c}\overline{g})\,. \tag{4}$$

If the singlet field $\overline{S}$ acquires a nonvanishing VEV $\langle\overline{S}\rangle$ [10], then $\overline{H}_u$, $\overline{H}_d$, $\overline{g^c}$ and $\overline{g}$ in $\overline{\Phi}$ gain supersymmetric masses

$$m_{\overline{\Phi}_{1/2}} \sim f(T)\,\langle\overline{S}\rangle\,. \tag{5}$$

Also, we have the soft SUSY breaking scalar masses, which are given by

$$m^2_{\overline{\Phi}_0} \sim f'(T) F^T \langle\overline{S}\rangle\,, \tag{6}$$

where $f'(T)$ denotes the derivative with respect to T. Therefore, the scalar particles in $\overline{H}_u$, $\overline{H}_d$, $\overline{g^c}$ and $\overline{g}$ have the masses squared $m^2_{\overline{\Phi}_{1/2}} \pm m^2_{\overline{\Phi}_0}$.

Since only the anti-generation fields $\overline{\Phi}$ couple to the T moduli, the fields $\overline{\Phi}$ behave as messenger fields in the framework of the gauge-mediated SUSY breaking scenario. It should be noted that the flavor dependence of $\langle T_i \rangle$ is not transmitted to the generation fields Φ. In the GUT-type models which accommodate the MSSM at low energies, $\langle \overline{S} \rangle$ and $\langle S \rangle$ are expected to be larger than 10^{16} GeV [10]. In this case these messenger fields will become sufficiently heavy compared to the electroweak scale. The other extra fields belonging to one set of the vector-like multiplet also become massive near or slightly above the intermediate energy scale via nonrenormalizable interactions [10]. On the other hand, due to vanishing F-terms of the U moduli, the generation fields Φ cannot behave as messenger fields. The messenger fields $\overline{\Phi}$ have the quantum number of the standard model gauge group. Therefore, integrating out the messenger sector gives rise to gaugino masses at one loop. Estimating one-loop diagrams, one finds that the gaugino masses induced are

$$m_{\lambda_i} \sim \frac{g_i^2}{16\pi^2} \Lambda \,, \tag{7}$$

where

$$\Lambda = \left| \frac{f'(T)}{f(T)} \right| F^T \,, \tag{8}$$

and the g_is are the gauge coupling constants ($i = 1, 2, 3$). The soft scalar masses in the low-energy MSSM sector, in which N_f sets of the generation fields $\Phi(\mathbf{27})$ remain light, arise at leading order from two-loop diagrams. Messenger fields, gauge bosons and gauginos take part in the internal lines of the two-loop diagrams. Consequently, the soft scalar masses induced are of the same order as the gaugino masses :

$$m_0 \sim m_{\lambda_i} \,. \tag{9}$$

Provided that Λ is $\mathcal{O}(100 \text{ TeV})$, the mass spectrum of superparticles is consistent with that in the MSSM. As mentioned above, the significant features of this scenario are that there are sufficient degeneracies among squarks (sleptons) to ensure adequate suppression of FCNC and that no new CP phases are induced in soft SUSY breaking parameters.

As a consequence of the worldsheet instanton effects, $f(T)$ is of the form

$$f(T) \propto e^{-\lambda T} \,, \tag{10}$$

where λ is a constant. $\mathrm{Re}\, T$ is related to the compactification radius R as $\mathrm{Re}\, T \sim R^2$ in units of the string scale. The string scale M_s is defined by $(\alpha')^{-1/2}$, where α' is the string tension. From Eq. (10), Λ in Eq. (8) becomes $\Lambda = \lambda F^T$. In view of

the fact that ImT corresponds to an axion-like field, it is adequate for us to require the periodicity of $f(T)$ in units of the string scale. In this context we postulate that $\lambda = \mathcal{O}(2\pi M_s^{-1})$. Thus, we have

$$m_{\lambda_i} \sim \frac{g_i^2}{8\pi} \times \frac{F^T}{M_s} \,. \tag{11}$$

With the scale $F^T/M_s = \mathcal{O}(20 \text{ TeV})$, we find that the gaugino masses are on the order of a few hundred GeV.

Now we proceed to discuss the gravitino mass. In the weakly coupled heterotic string, the Kähler potential is given by [11]

$$K = -\ln(D + D^*) - 3\ln(U + U^*) - 3\ln(T + T^*) + \cdots \,. \tag{12}$$

Here the dots represent the higher-order terms. Using the above Kähler potential and assuming a vanishing cosmological constant, we obtain the gravitino mass

$$m_{3/2} = \frac{F^T}{2\mathrm{Re}\,T} \sim \frac{F^T}{2M_s} \,. \tag{13}$$

In string theory, the compactification radius is expected to be around the inverse string scale. From Eqs. (9), (11) and (13) we obtain the phenomenologically viable relations

$$m_0 \sim m_{\lambda_i} \sim \frac{m_{3/2}}{10} \,. \tag{14}$$

Since the gaugino mass and the scalar mass are also induced by gravitational interactions, we must study whether or not the gauge-mediated contribution is dominated by a gravity-mediated contribution. In the weakly coupled heterotic string, the gauge-kinetic function in the observable sector is of the form $f_6 = D + \epsilon T$, and we have $D \gg \epsilon T$ in the weak coupling region. The second term in f_6 comes from the string one-loop correction and ϵ is a small constant fixed by gauge and gravitational anomaly[11][12]. The gravity-mediated contribution to the gaugino mass is given by

$$m_\lambda^{(\mathrm{gr})} = \sum_{m=D,T,U} \frac{F^m \partial_m f_6}{2\mathrm{Re}\, f_6} \sim \frac{\epsilon F^T}{2\mathrm{Re}\, D} \,. \tag{15}$$

Since we have $\mathrm{Re}\, D = 4\pi/(g_i^2)$ at the unification scale, Eq. (15) cac be rewritten as

$$m_{\lambda_i}^{(\mathrm{gr})} \sim \frac{g_i^2}{8\pi} \times \frac{\epsilon F^T}{M_s} \,. \tag{16}$$

From Eqs. (11) and (16) the ratio of $m_{\lambda_i}^{(\mathrm{gr})}$ to m_{λ_i} becomes

$$\frac{m_{\lambda_i}^{(\mathrm{gr})}}{m_{\lambda_i}} \sim \epsilon \ll 1 \,. \tag{17}$$

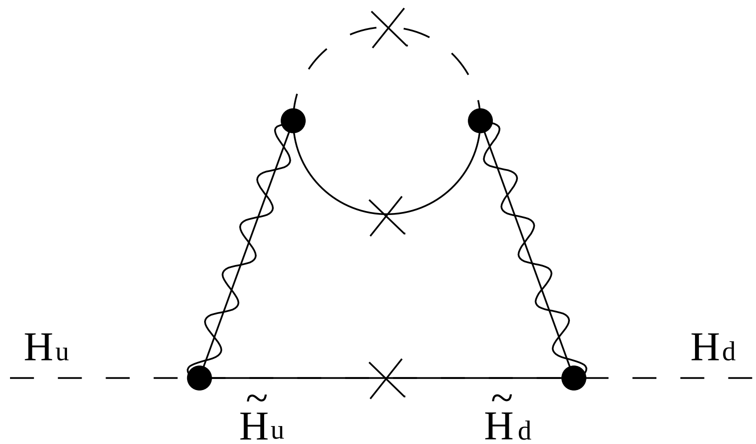

Figure 1: The $B\mu$ term is generated in the two-loop diagram.

Further, the gravity-mediated contribution to the scalar mass is given by

$$m_0^{(\mathrm{gr})} = \sqrt{\frac{\epsilon \mathrm{Re}T}{\mathrm{Re}D}} m_{3/2} \sim \frac{F^T}{M_s}\sqrt{\epsilon \frac{g_i^2}{16\pi}} \tag{18}$$

up to a one-loop correction [6]. Then the ratio of $m_0^{(\mathrm{gr})}$ to m_0 becomes

$$\frac{m_0^{(\mathrm{gr})}}{m_0} \sim \sqrt{\epsilon \frac{4\pi}{g_i^2}} \sim 5\sqrt{\epsilon} \ll 1\,. \tag{19}$$

where we have taken $g_i^2/(4\pi) \sim 1/25$ at the unification scale. As can be deduced from Eqs. (17) and (19), the gauge-mediated contribution to the gaugino mass and scalar mass are dominant compared to the gravity-mediated contribution.

Finally, we discuss the μ problem. In the present model the μ term comes from the first term in Eq. (3) with $\mu \sim h(U)\langle S \rangle$. The $B\mu$ term is generated in the two-loop diagram as shown in Fig.1. The messenger fields ($\overline{\Phi}$) propagate in the innermost loop. The external lines are the scalar fields H_u and H_d and the remaining internal line has the fermion mass insertion $\mu H_u H_d$. The ratio of $B\mu$ to μ^2 becomes

$$\frac{B\mu}{\mu^2} \sim 8\left(\frac{g_2}{4\pi}\right)^2 \frac{m_{\lambda_2}}{\mu} \ln\left(\frac{m_{\lambda_2}}{\mu}\right) \sim \mathcal{O}(1)\,, \tag{20}$$

provided that $m_{\lambda_2}/\mu \sim \mathcal{O}(10)$. Introducing a certain type of flavor symmetry, we can obtain $\mu \sim h(U)\langle S \rangle \sim \mathcal{O}(100\ \mathrm{GeV})$ [10]. Thus, the μ problem is solved.

In conclusion, we propose a new model of SUSY breaking mediation on the basis of the weakly coupled heterotic string on the Calabi-Yau compactification. In this model, SUSY breaking is mediated to the MSSM sector by two phases. In the first phase, SUSY breaking in the hidden sector is transmitted to anti-generation fields

via gravitational interactions. Subsequent transmission of SUSY breaking occurs via gauge interactions. Although the moduli fields are charged under the flavor symmetries, due to the flavor-blind nature of gauge interactions, we obtain the universal soft scalar masses. The mass spectra of superparticles obtained here are phenomenologically viable.

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